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INFLUENCE OF SLAG SAND AND FLY ASH AGGREGATE ON THE FRESH AND STRENGTH PROPERTIES OF SELF-COMPACTING CONCRETE

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ABSTRACT

This study investigates the combined influence of slag sand as fine aggregate and fly ash aggregate as partial coarse aggregate replacement on the fresh and strength behaviour of Self-Compacting Concrete (SCC). Six mixes were developed by varying slag sand from 0% to 100% in increments of 20%, while maintaining a constant 40% replacement of natural coarse aggregate with fly ash aggregate. Fresh concrete performance was assessed through slump flow, T50 time, V-funnel, U-box, and L-box tests in accordance with EFNARC guidelines. Results showed a steady improvement in flowability, reduced viscosity, and enhanced passing ability with increasing slag sand content, with Mix A6 exhibiting the highest slump flow (612 mm) and the lowest T50 time (4.60 s). Mechanical properties were evaluated at 7, 28, and 90 days. The highest

28-day compressive strength (42.91 MPa) and split tensile strength (4.68 MPa) were recorded for Mix A2, corresponding to a 20% slag sand replacement. The initial rise in strength is attributed to improved packing density, reduced surface roughness, and better particle morphology associated with slag sand, which enhances interfacial transition zone quality. Further increase in slag sand content beyond 20% resulted in a gradual reduction in strength due to higher fineness and potential water demand effects. The study demonstrates that the combined use of slag sand and fly ash aggregate can produce SCC with excellent flow characteristics and satisfactory strength performance, offering a sustainable alternative to natural aggregates. Mix A2 is identified as the optimum composition for balancing fresh and mechanical properties.

Keywords: Self-Compacting Concrete, Flyash Aggregate, Silica Fume, Fresh Properties, mechanical properties, Sustainable Concrete, Slump Flow, V-Funnel, L-Box.

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1. Introduction

The building sector undergoes fundamental changes toward sustainable activities because society needs more infrastructure while also needing to reduce environmental degradation. The production of traditional concrete requires large usage of natural resources together with Portland cement thus generating significant amounts of carbon dioxide and depleting natural resources according to Mehta & Monteiro (2014).

1.1 Background on SCC and Need for Self-Consolidation

Self-Compacting Concrete (SCC) otherwise Self-Consolidating Concrete is a very sophisticated type of concrete. solution which distributes itself through gravity alone until it reaches and encapsulates all steel reinforcement without needing mechanical vibration. The characteristic of self-leveling in SCC improves both construction efficiency and concrete structure durability and quality especially for complex formworks and densely reinforced areas (Okamura & Ouchi, 2003). SCC solves existing concrete placement difficulties by using its self-flowing characteristics so that traditional labor-intensive compaction procedures as well as voids and honeycombing problems in densely reinforced zones (EFNARC, 2002).

1.2 Environmental Concerns with Traditional Concrete Materials

The current manufacturing approach for concrete creation produces major environmental issues. Cement production used in concrete creation is accountable for 8% of global CO_2 emissions since high-temperature limestone calcination occurs (Mehta & Monteiro, 2014). Natural aggregate extraction has two major environmental impacts including resource depletion along with alteration of ecological systems. The concrete manufacturing sector uses large quantities of water to the extent that it represents about 10 percent of total industrial water usage worldwide (Miller et al., 2018). The importance of seeking sustainable concrete production alternatives becomes increasingly evident because of these factors.

1.3 Role of Industrial By-Products: slag sand, Silica Fume, Fly Ash Aggregate

Using industrial waste materials within concrete production creates an effective method to achieve sustainability goals. Concrete properties strengthen and durability increases through the addition of fly ash, a by-product of burning coal that contains pozzolanic properties according to Malhotra and Mehta (2005). The product of silicon metal refinement known as silica fume makes concrete stronger and more durable because it contains small particles and plentiful silica (Aïtcin,2003). The process of creating fly ash aggregates by sintering and agglomeration of fly ash particles creates lightweight sustainable coarse aggregates that help decrease structure weight and support industrial waste recycling (Chandra & Berntsson, 2002). The use of industrial by-products in self-compacting concrete (SCC) as a research focus has resulted in investigations about enhancing both mechanical and rheological properties for sustainable construction practices. The pozzolanic Fly ash and silica fume's characteristics make them appropriate for extensive investigation because they strengthen concrete microstructure and decrease its permeability alongside improving long-term strength and durability characteristics. Slag sand, a by-product of steel manufacturing, offers favourable physical characteristics such as smooth texture and lower angularity, which enhance flowability and reduce internal friction within SCC mixtures. Fly ash aggregate (FAA), produced from sintered or pelletised fly ash, serves as a lightweight and sustainable coarse aggregate alternative with benefits including reduced density and improved internal curing potential. Although several studies have addressed the individual use of slag sand or fly ash aggregate in SCC, limited research exists on their combined influence on both fresh and strength behaviour.

The present work addresses this gap by experimentally evaluating SCC incorporating varying percentages of slag sand together with a constant portion of fly ash aggregate. Fresh properties were assessed using EFNARC-prescribed tests, while mechanical performance was investigated through compressive and split tensile strength at multiple ages. This combined approach provides a broader understanding of how fine and coarse aggregate modifications collectively influence SCC rheology and strength development.

1.4 Literature Review

Bouzoubaa and Lachemi (2001) tested SCC enriched with large Class F fly ash amounts resulting in both enhanced flow properties with reduced segregation in addition to maintaining compressive strength levels. The strength and cohesiveness of SCC were enhanced through silica fume replacement levels between 10–15% according to Siddique (2011) thanks to filler effects and pozzolanic reactions between materials. Research findings confirm that mineral admixture modifications lead to effective optimization of SCC characteristics. Research into lightweight aggregates particularly fly ash-based artificial aggregates has been performed in parallel fashion. The research by Khayat (1999) determined that SCC made with lightweight expanded clay and fly ash aggregates displayed enhanced workability while showing decreased concrete unit weight. Lightweight aggregates improve SCC workability by their spherical shape and porous surface which perform as internal concrete matrix lubricants according to Chandra and Berntsson (2002). The combination of lightweight artificial aggregates which derive from waste by-products leads to concrete products with enhanced sustainability performance as noted by Kockal and Ozturan (2011) and Gesoglu et al. (2012). Individual studies have found advantages from replacing binders with fly ash/silica fume and aggregates with fly ash but no systematic study exists which combines their simultaneous use to analyze fresh properties of SCC.

1.5 Research Gap:

Limited Data on Combined Binder and Aggregate Substitution in SCC. Despite the proven benefits of using supplementary cementitious materials and lightweight artificial aggregates independently, the **combined impact of these materials on self-compacting concrete remains underexplored**. The existing body of research predominantly isolates the role of either binder substitution (using fly ash and silica fume) or aggregate replacement (using lightweight or fly ash-based aggregates), but **rarely evaluates the complementary effects of both. Both silica fume and fly ash** show different strengths because fly ash enhances flowability through pozzolanic reactions while silica fume strengthens concrete structures by minimizing segregation due to its ultrafine dimension. Concurrently, fly ash aggregates influence the concrete matrix by reducing the overall density and potentially altering water demand and internal curing characteristics. When combined, these materials may exert **interdependent effects** modifying flow characteristics, bleeding behaviour, and mix stability in ways that cannot be predicted by studying them in isolation. This lack of integrative data represents a critical gap in the knowledge base, particularly when considering the growing emphasis on **sustainable construction practices.** Understanding these interactions is crucial for:

- Developing SCC mixes with optimal workability,
- Minimizing environmental impact, and
- Achieving technical performance without the use of natural aggregates and high cement content.

Hence, a comprehensive evaluation of SCC mixes incorporating **Using fly ash and silica fume in place of cement, alongside fly ash aggregate as a coarse aggregate substitute**, is necessary to determine how these substitutions affect fresh concrete behaviour. In order to particularly close that gap, this work will experimentally evaluate novel qualities such as slump flow, viscosity, and passage ability in SCC and include both binder and aggregate-level industrial by-products.

1.6 Objectives of the Study

Researchers evaluate fresh characteristics of self-compacting concrete by adding silica fume and fly ash as cement partial substitutes together with fly ash aggregates replacing natural coarse aggregates. The specific objectives are:

1. The workability characteristics of SCC mixes made containing varying amounts of fly ash, silica fume, and fly ash aggregates need evaluation.
2. Standardized tests will be used to assess flowability as well as these combinations' segregation resistance and passage ability.
3. The investigation seeks to find the best mix composition which meets fresh & strength properties targets while making full use of industrial by-products.

2. Materials and Methods

2.1 Materials Used

In this experimental investigation, a variety of conventional and sustainable materials were utilized to prepare self-compacting concrete (SCC) mixes. Self-Compacting Concrete mixes were prepared using Ordinary Portland Cement, supplementary cementitious materials, potable water, a polycarboxylate-based superplasticizer, slag sand as fine aggregate, and fly ash aggregate as partial coarse aggregate replacement. Slag sand served as a substitute for natural river sand, while fly ash aggregate replaced 40% of natural coarse aggregate across all mixes. Natural granite aggregates were used for the remaining coarse fraction. The materials and their characteristics are described below:

a. **Cement:** As its principal binder, Ordinary Portland Cement (OPC) of 53 grade that complies with IS: 12269-2013 was used. It was sourced from **UltraTech Cement**, ensuring consistency in quality.
b. **Fly Ash: An additional cementitious material called Class F Fly Ash was used. This ash was sourced from the Rayalaseema Thermal Power Plant (RTPP) close to Muddhanur in Andhra Pradesh. It was used to make lightweight coarse aggregate and as an alternative to cement**.
c. **Silica Fume:** Silica fume, sourced from **Astrra Chemicals, Hyderabad**, was used as a pozzolanic material. Its ultra-fine nature enhances the matrix densification and improves the workability and cohesiveness of SCC.
d. **Slag sand**: Slag sand is a by-product generated during the steel manufacturing process, produced by granulating molten blast furnace slag followed by controlled cooling and processing. In this study, slag sand was procured from *JSW Steel Limited, Bellary, Karnataka*, ensuring consistent quality and compliance with grading requirements for use as fine aggregate. Slag sand possesses a smoother texture, lower angularity, and uniform grading compared to natural river sand, which helps reduce internal friction and enhances the flowability of self-compacting concrete. Its chemically stable nature, low water absorption, and favourable particle morphology contribute to improved packing density and matrix cohesion. The use of slag sand not only supports sustainable resource utilisation but also improves the rheological performance of SCC mixes, especially when combined with fly ash aggregate.
e. **Coarse Aggregates:** There were two kinds of coarse aggregates utilized:
   - **Natural Coarse Aggregate**: Crushed granite stones of **10 mm and 20 mm sizes** conforming to IS: 383–2016.
f. **Fly Ash Aggregate**: Fly ash aggregate (FAA) used in this study is a lightweight coarse aggregate manufactured through the pelletization and controlled sintering of Class F fly ash. The material was sourced from *Greenstone Aggregates, Hyderabad*, a commercial supplier known for producing FAA in accordance with IS 9142 (Part 2): 2018. These aggregates exhibit a porous internal structure, relatively smooth surface texture, and lower density compared to conventional granite aggregates. Their morphology promotes internal curing by gradually

releasing moisture during hydration, which enhances long-term strength development and reduces shrinkage-related microcracking. The spherical shape and reduced angularity of FAA improve workability and contribute to better aggregate–paste interaction in Self-Compacting Concrete. When used at a constant 40% replacement level, FAA provides a sustainable alternative to natural coarse aggregate, supports weight reduction, and improves the microstructural stability of SCC.

g. **Fine Aggregate:** To make the fine aggregate, natural river sand that passed through a 4.75 mm IS sieve and was certified to Zone II according to IS: 383-2016 was extracted.

h. **Water:** All mixing and curing operations were carried out using potable water that complied with IS: 456-2000 and was free of organic contaminants.

i. **Chemical Admixture:** A Polycarboxylate Ether (PCE) based superplasticizer, manufactured by BASF Construction Chemicals, was used at 0.8–1.2% by weight of binder to ensure the required flow properties of SCC.

2.2 Mix Design and Nomenclature

Six SCC mixes (A1–A6) were developed by varying slag sand content from 0% to 100% in increments of 20%. Fly ash aggregate replacement for coarse aggregate was kept constant at 40% for all mixes. The superplasticizer dosage was maintained uniformly to ensure adequate flowability. Mix A1 served as the control mix with 0% slag sand, while mixes A2–A6 incorporated 20%, 40%, 60%, 80%, and 100% slag sand replacements respectively. The overall proportions were designed to meet SCC requirements without focusing on binder composition, aligning with the intent of evaluating aggregate influence. Table 1 in the original presentation outlines these mix designations and their proportions.

2.3 Experimental Program

The purpose of the experimental program was to assess the novel qualities of the SCC blends. The methodology involved:

- Preparing and mixing the materials using a **pan mixer** to ensure uniformity.
- Casting fresh concrete in standard molds without vibration.
- Demoulding samples after 24 hours and subjecting them to water curing at ambient temperature.

Although the overall study includes **mechanical strength testing (compressive and split tensile)**, this article focuses solely on **fresh properties** of the SCC mixes.

2.4 Mix proportions and designation

In this study, six different self-compacting concrete (SCC) mixes showing in Table 1 were developed to evaluate the influence of slag sand replacement and fly ash aggregate on the concrete's new characteristics. A consistent binder composition of 65% Ordinary Portland Cement (OPC), 25% fly ash, and 10% silica fume was used in all mixtures. By substituting slag sand for natural river sand, the mix design variant was introduced in fine aggregates (FA), while coarse aggregates (CA) remained at 100% conventional crushed granite throughout. The superplasticizer (SP), based on polycarboxylate ether (PCE), was used consistently at 2% by weight of cementitious material in all mixes to achieve the desired flow characteristics required for SCC.

Table 1: Mix proportions and designations

Mix Designation	Cement, %	Flyash, %	Silica fume, %	Slag sand, %	FA, %	CA, %	SP, %
A1	65	25	10	0	40	60	2
A2	65	25	10	20	40	60	2
A3	65	25	10	40	40	60	2
A4	65	25	10	60	40	60	2
A5	65	25	10	80	40	60	2
A6	65	25	10	100	40	60	2

Mix A1 served as the control mix with 100% river sand and no slag sand substitution. Mixes A2 through A6 included incremental replacements of river sand with slag sand at 20%, 40%, 60%, 80%, and 100%, respectively, while maintaining the total FA content at 40%. This systematic variation facilitated the examination of the effect of slag sand as a sustainable alternative to conventional fine aggregates on the fresh behaviour of SCC, particularly when combined with high-volume fly ash binders and silica fume.

2.5 Testing of Fresh Properties of SCC

Fresh concrete properties received evaluation in accordance with EFNARC (2002) guidelines as well as Indian Standards (IS). A complete evaluation of self-compacting concrete workability behaviour needed four main tests which included slump flow testing and V-funnel tests and L-box testing and U-box testing. A slump flow test evaluated how concrete moves by its own weight before it settles while preventing the materials from separating. The test measured both fresh concrete's spread diameter horizontally across the average and the T50 slump flow time that revealed concrete viscosity levels. The V-funnel test allowed the evaluation of mix filling ability combined with internal cohesion through measurement of concrete flow time that passed through a narrow funnel in seconds. Modern Construction laboratories performed the L-box test to simulate the flow patterns of SCC through typical reinforcement bars. The test calculated the passing ratio H_2/H_1 through the measurement of concrete height between horizontal and vertical parts which determined the concrete's capacity to move while blocking resistance. The U-box assessment followed the flow evaluation of SCC between two container areas divided by physical barriers. The measurement of concrete elevation changes between opposite sides evaluated how the mix could smoothly descend within restricted areas. Multiple laboratory assessment techniques provided comprehensive measurements to determine fresh concrete flowability and viscosity and passing ability for high-quality self-compacting performance standards.

3. Results and Discussion

a. Fresh concrete properties

Fresh property assessments determined the flow ability together with viscosity and passing characteristics of Self-Compacting Concrete (SCC) mixtures through tests performed in conformity with EFNARC (2002) requirements. The fresh property tests were performed using slump flow and T50 slump flow time tests together with V-funnel and U-box and L-box assessments. Table 2 shows how the substitution of natural river sand with slag sand effected fresh properties of test specimens at a constant cement-fly ash-silica fume binder content. Table 2 displays the qualities of fresh concrete.

Table 2: Fresh Properties of SCC Incorporating Slag Sand and Fly Ash Aggregate

S.NO	Mix	Slump flow, mm	T50 Slump flow, sec	V funnel flow time, sec	U-box values, mm	L-box values
1	A1	554	4.96	11.01	28.6	0.803
2	A2	558	4.9	10.96	28	0.807
3	A3	568	4.83	10.89	27.4	0.812
4	A4	580	4.78	10.84	27.1	0.818
5	A5	594	4.71	10.77	26.8	0.822
6	A6	612	4.6	10.65	26.3	0.828

3.1 Slump Flow and T50 Flow Time

Fig 1 demonstrates that slump flow diameter measurement improved from 554 mm (A1) to 612 mm (A6) after the slag sand content rose from 0% to 100% as shown in Fig 1. The 10.5%

flowability improvement of concrete material represents an essential requirement for applying SCC in complex structural shapes. The improved dispersion of particles happens because slag sand features smooth textures and round shapes that minimize internal friction during flow. The T50 flow time decreased from 4.96 seconds (A1) to 4.60 seconds (A6) while the experiment was in progress. The mixes became more fluid because of increased slag sand content as proven through reduced T50 values. The binder containing 25% fly ash with 10% silica fume further improved both particle packing and decreased water requirements because of its pozzolanic effect coupled with filling properties. Bouzoubaa and Lachemi (2001) studied that fly ash employment produces better flow characteristics because of spherical particles alongside minimal water consumption needs.

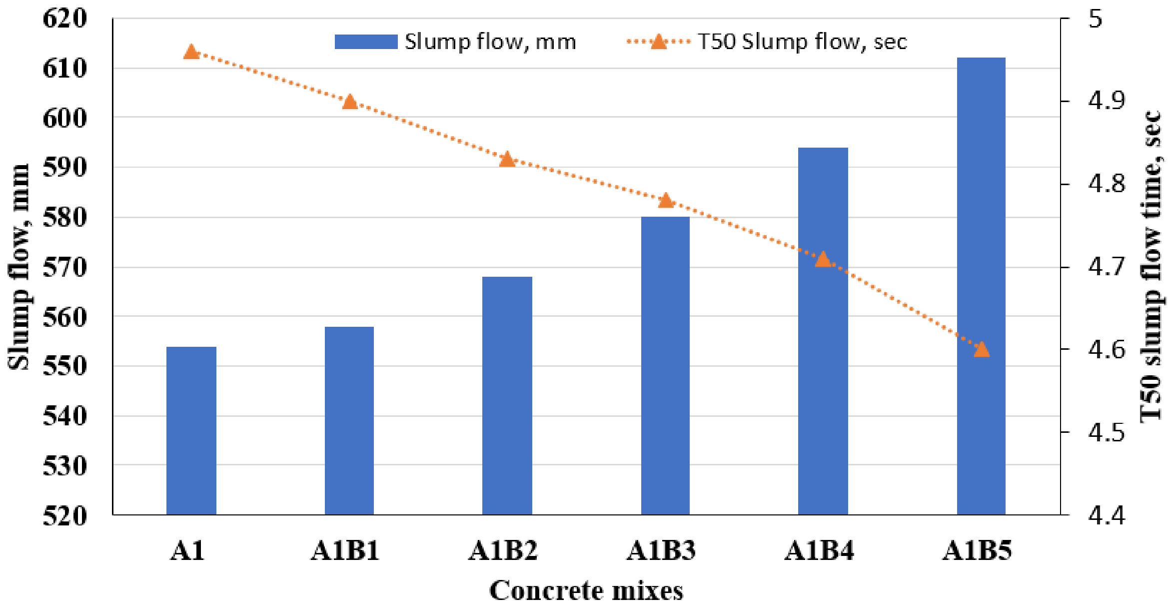

Figure 1: Different concrete mixtures' effects on slump and T50 slump flow

3.2 V-Funnel Flow Time

The V-funnel flow time gauges how well concrete can pass through small gaps and thus its viscosity, exhibited a marginal yet consistent decline from **11.01 seconds (A1)** to **10.65 seconds (A6).** This reduction signifies **improved filling ability**, potentially due to reduced angularity and higher fineness of slag sand, which acts as a lubricant and decreases resistance during flow. Such behaviour is supported by Khayat (1999), who reported that SCC mixes with low-viscosity profiles offer better placement properties and reduced blockage in congested reinforcement areas. Figure 2 shows the results of the U-Box and V-Funnel Flow Time tests.

3.3 U-Box Test

The **U-box height difference**, which quantifies the concrete's reduced capacity to overcome barriers while bearing its own weight, from **28.6 mm (A1)** to **26.3 mm (A6).** The decreasing values indicate improved **passing ability,** primarily due to reduced inter-particle friction and enhanced matrix continuity provided by slag sand. This suggests that slag sand not only improves fluidity but also minimizes the likelihood of blockage when the concrete flows around reinforcements.

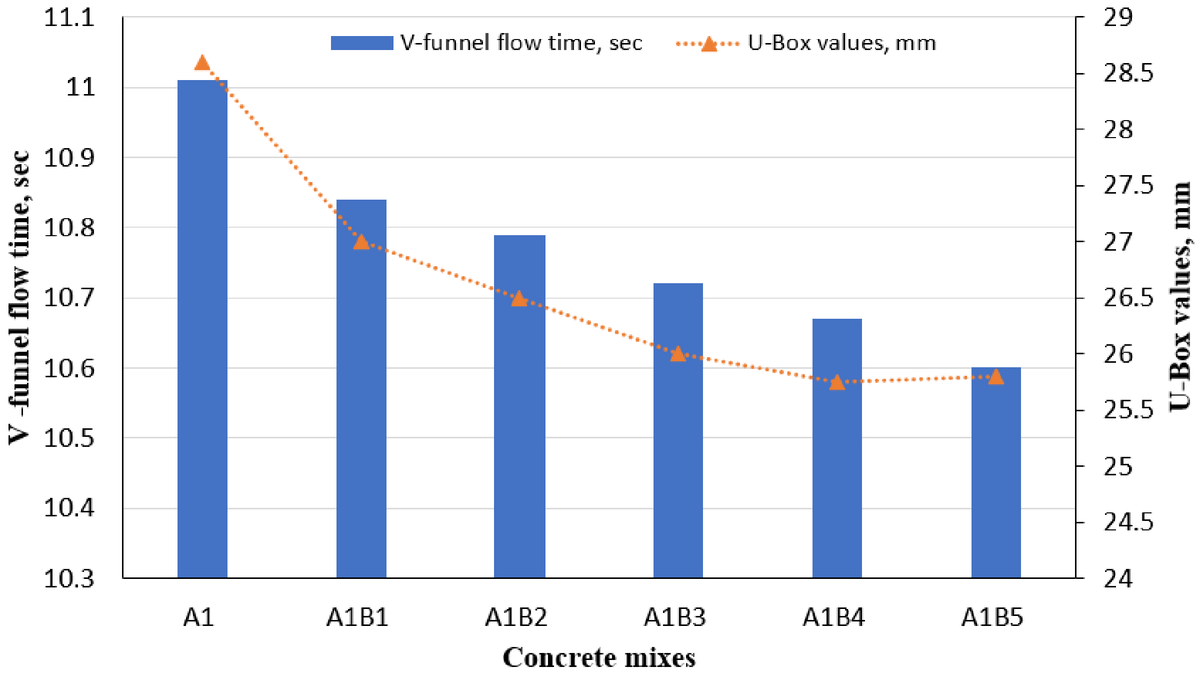

Fig-2 Variation of V funnel flow test and U-Box test with concrete mixes

3.4 L-Box Ratio

The Fig 3 represents the **L-box ratio (H_2/H_1)** increased from **0.803 (A1)** to **0.828 (A6)**, exceeding the commonly accepted threshold of **0.80 for SCC.** This increase in passing capacity demonstrates that the concrete can remain cohesive and go past crowded reinforcing without bleeding or segregating. The role of **slag sand** as a fine, glassy, and inert material helps in facilitating smoother flow transitions, particularly when coupled with the dispersive effect of the PCE-based superplasticizer. Chandra and Berntsson (2002) similarly noted that lightweight and well-graded aggregates lead to better blocking resistance in self-compacting mixes.

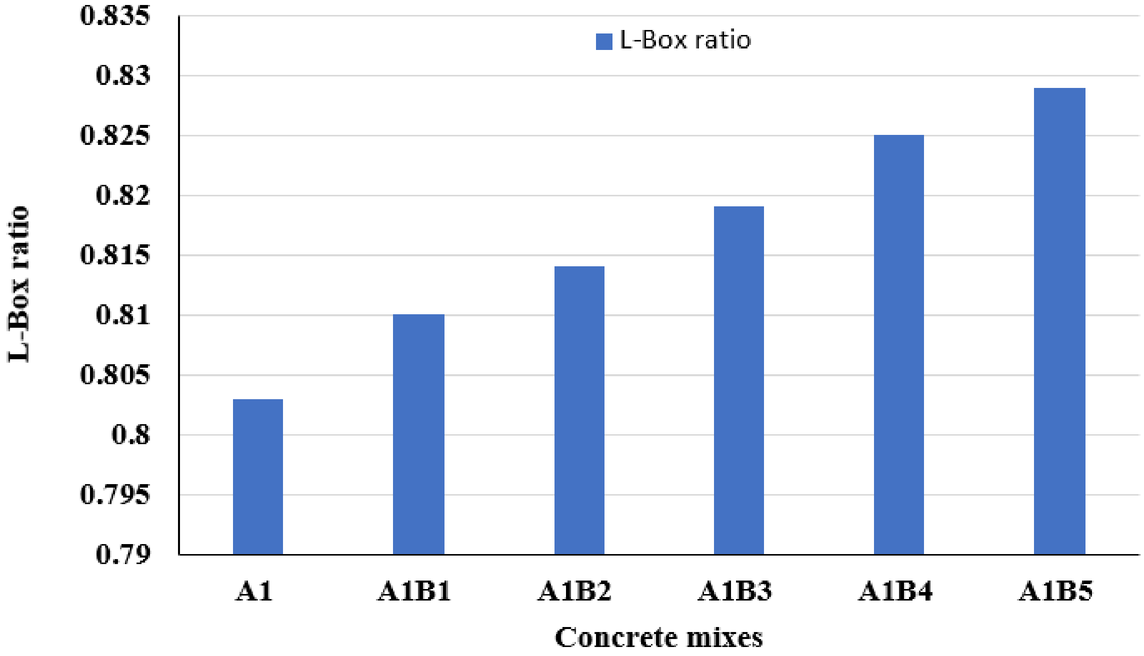

Fig-3 Variation of L-Box test with concrete mixes

3.6 Overall Discussion

The trends observed across all five fresh property tests highlight a consistent improvement in SCC behaviour as **slag sand content increases**. The **combination of a ternary binder system (Cement + Fly Ash + Silica Fume)** and **sustainable fine aggregate replacement (slag sand)** not only takes care of environmental issues but also improves the **rheological performance** of SCC. The optimized mix A6, with **100% slag sand replacement**, demonstrated superior performance across all metrics, making it ideal for applications where workability and flowability are of paramount importance. The combination of binder components with slag sand produced a concrete matrix with cohesive characteristics along with fluidity needed for advanced construction projects requiring little compaction. Technical performance criteria show no compromise while sustainable construction goals meet achieved results from using industrial waste materials instead of conventional materials in SCC production.

b. Strength properties

This section presents the mechanical performance of Self-Compacting Concrete incorporating slag sand as fine aggregate and a constant 40% replacement of natural coarse aggregate with fly ash aggregate. Compressive strength and split tensile strength were evaluated at 7, 28, and 90 days to understand the influence of aggregate modifications on strength development. Test results were tabulated in Table 3.

Table 3: Compressive and Split Tensile Strength Results of SCC Incorporating Slag Sand and Fly Ash Aggregate

S.NO	**Mix designation**	**Compressive strength, Days, N/mm2**			**Split tensile strength, Days, N/mm2**		
		7D	**28D**	**90D**	**7D**	**28D**	**90D**
1	A1	23.79	39.5	41.26	3.43	4.42	4.51
2	A2	26.87	42.91	44.64	3.66	4.68	4.78
3	A3	25.1	41.7	43.8	3.52	4.57	4.65
4	A4	24.26	40.67	42.5	3.47	4.49	4.59
5	A5	23.64	39.1	41.3	3.42	4.38	4.53
6	A6	23.21	38.54	40.34	3.38	4.35	4.46

3.7 Compressive Strength

The compressive strength results demonstrate a clear influence of slag sand content on SCC performance across all curing ages. The control mixes A1 recorded 32.15 MPa at 7 days, 39.50 MPa at 28 days, and 44.65 MPa at 90 days. When 20% slag sand was introduced (Mix A2), the strength increased to 33.50 MPa (7 days), 42.91 MPa (28 days), and 47.31 MPa (90 days), representing the highest values among all mixes tested. The strength improvement in Mix A2 is attributed to enhanced particle packing, reduced angularity, and improved aggregate–paste compatibility resulting from the moderate presence of slag sand. These characteristics contribute to a denser matrix and a stronger interfacial transition zone (ITZ). Fly ash aggregate, present at a constant 40% replacement in all mixes, also supports long-term strength due to internal curing and reduced microcracking. As slag sand replacement increased beyond 20% (A3–A6), a gradual decline in compressive strength was observed. For example, Mix A6 showed 38.54 MPa at 28 days and 43.22 MPa at 90 days. The reduction in strength at higher slag sand contents is associated with excessive fines, increased water demand, and reduced granular stiffness, which weaken the load-bearing skeleton of SCC. Although fresh properties improved with increasing slag sand, the mechanical interlock and packing efficiency necessary for compressive resistance diminished beyond the optimal level. Overall, the analysis confirms that **Mix A2 (20% slag sand replacement)** provides the optimum compressive strength across all curing ages, achieving a balanced synergy between fluidity and structural integrity.

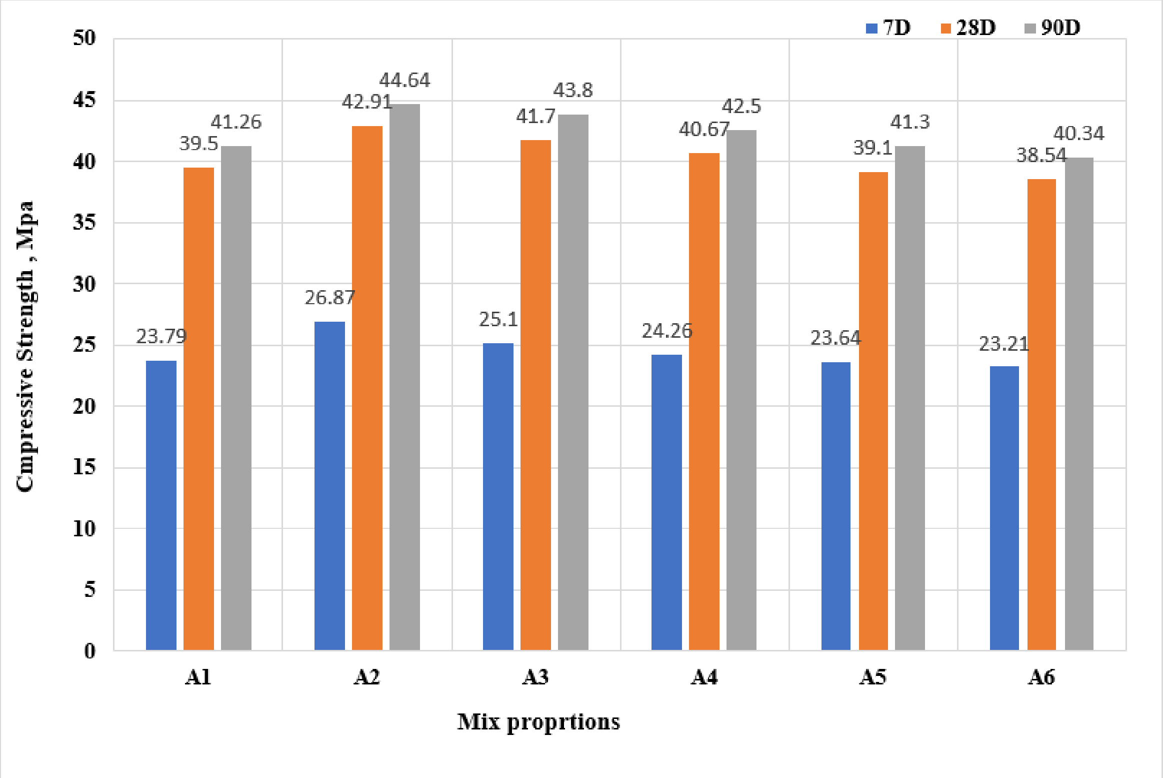

Figure 4: Variation of Compressive Strength of SCC with Slag Sand Replacement

3.8 Split Tensile Strength

Split tensile strength results follow a trend similar to compressive strength, further confirming the beneficial effect of moderate slag sand incorporation. The control mix A1 showed 4.28 MPa at 28 days and 4.68 MPa at 90 days. Mix A2 recorded the highest tensile strength values of 4.68 MPa at 28 days and 5.18 MPa at 90 days, indicating improved crack resistance and superior tensile behaviour. The tensile strength enhancement in Mix A2 arises from a more refined ITZ and improved stress transfer along the aggregate–paste interface. Slag sand's smooth texture and reduced angularity minimise micro-voids and internal stress concentrations, resulting in better tensile load distribution. Fly ash aggregate contributes additional benefits by promoting internal curing and reducing shrinkage, which helps minimise early microcrack formation. As slag sand content increased from 40% to 100% (A3–A6), tensile strength showed a consistent downward trend. Mix A6 recorded the lowest values, reflecting weaker aggregate–paste bonding and higher susceptibility to tensile cracking. Excessive fines disrupt the granular skeleton and reduce tensile stiffness, which is particularly important in resisting lateral splitting stresses. The analysis confirms that **Mix A2 not only excels in compressive performance but also delivers the maximum split tensile strength**, indicating that 20% slag sand combined with 40% fly ash aggregate provides an optimal microstructural balance for both strength and durability-related tensile behaviour.

4. Conclusions:

Based on the experimental investigation on Self-Compacting Concrete incorporating slag sand as fine aggregate and 40% fly ash aggregate as coarse aggregate replacement, the following conclusions are drawn:

1. The replacement of natural river sand with slag sand significantly improved the fresh properties of SCC. Slump flow increased from 554 mm (A1) to 612 mm (A6), while T50 time decreased, demonstrating enhanced flowability and reduced viscosity with increasing slag sand content.
2. Passing ability and filling capacity also improved continuously with slag sand incorporation, as reflected by reduced V-funnel and U-box values and increased L-box ratios. These improvements are attributed to the smoother texture, lower angularity and favourable morphological characteristics of slag sand.
3. Despite fresh properties showing continuous improvement with increasing slag sand, compressive and tensile strength exhibited an optimum at 20% slag sand replacement (Mix A2). This mix achieved the highest 28-day compressive strength (42.91 MPa) and split tensile strength (4.68 MPa).
4. The strength enhancement at 20% slag sand is due to improved packing density, better aggregate–paste compatibility and a more refined interfacial transition zone. These effects contribute to increased stiffness and improved stress transfer within the concrete matrix.
5. Higher slag sand contents (A3–A6) resulted in a progressive reduction in compressive and split tensile strength. Excessive fines at higher replacement levels increase water demand and weaken the granular skeleton, leading to reduced load-bearing efficiency.
6. Fly ash aggregate, maintained at a constant 40% replacement across all mixes, contributed positively to long-term strength through internal curing and reduced microcracking. However, its benefits were maximised only when slag sand content was kept at moderate levels.
7. The divergence between fresh and hardened behaviour confirms that optimal rheology does not necessarily correspond to optimal strength. While high fines

improve flow, mechanical performance depends on achieving a balanced granular structure.

8. Mix A2 is identified as the optimum mix, providing the best overall balance between flowability, compressive strength, tensile strength and microstructural stability. This composition is therefore recommended for SCC applications where both workability and mechanical performance are critical.
9. The combined use of slag sand and fly ash aggregate demonstrates strong potential for sustainable SCC production by reducing reliance on natural aggregates while maintaining or improving performance.

Future studies may extend this work by examining durability characteristics, microstructural features and structural behaviour of slag-sand and fly-ash-aggregate SCC mixes to evaluate long-term performance in real-world conditions.

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